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FINAL REPORT

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

TEXAS INSTRUMENTS INCORPORATED
Equipment Group
Post Office Box 6015
Dallas, Texas 75222

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CFNTER
Alexandria, Virginia 22314

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. 6F10
ARPA Order No. 2551

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Work performed on Contract Number F08606-76-C-0011 has been reported in detail in a series of ten technical reports. This final report summarizes the material covered in each of the technical reports and discusses the conclusions obtained. The four tasks in the program included the following:

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> Matched Filter
> Dispersive Adaptive Filter
> Complex Cepstrum
> Variable Frequency Magnitude
> Higher Mode Surface Waves
> Depth Determination.

20. continued

- Evaluate available data from the Iranian Long Period Array (ILPA) and the Seismic Research Observatories (SRO), and evaluate the detection capability of the Korean Seismic Research Station (KSRS) using an optimum seismic detector.

- Evaluate the detection capability of a global seismic network of arrays, and determine the effectiveness of an adaptive beamforming algorithm as a short-period (SP) detector applied to off-line beamed SP KSRS data.

- Determine the improvements in long-period signal estimation by cascading previously developed techniques, developing a seismic filter which adapts to azimuthal wandering of incident signals, and designing a long-period adaptive filter which incorporates a surface wave group velocity dispersion relation.

- Evaluate the discrimination capability of an expanded interactive graphics system for the PDP-15 computer which includes complex cepstrum and frequency domain spectral analysis, and examine the depth determination capability of first-zone higher mode surface waves.

ABSTRACT

Work performed on Contract Number F08606-76-C-0011 has been reported in detail in a series of ten technical reports. This final report summarizes the material covered in each of the technical reports and discusses the conclusions obtained. The four tasks in the program included the following:

- Evaluate available data from the Iranian Long Period Array (ILPA) and the Seismic Research Observatories (SRO), and evaluate the detection capability of the Korean Seismic Research Station (KSRS) using an optimum seismic detector.

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SECTION I

INTRODUCTION

This final report summarizes work performed under Contract
Number F08606-76-C-0011, entitled VELA Network Evaluation and Automatic
Processing Research, by Texas Instruments Incorporated at the Seismic Data
Analysis Center (SDAC) in Alexandria, Virginia. This program, which was
conducted during the period from 1 July 1975 to 30 October 1976, consisted of
the following four tasks:

- Evaluate available data from the Iranian Long Period Array
  (ILPA) and the Seismic Research Observatories (SRO), and
  evaluate the detection capability of the Korean Seismic Re-
  search Station (KSRS) using an optimum seismic detector.

- Evaluate the detection capability of a global seismic network
  of arrays, and determine the effectiveness of an adaptive
  beamforming algorithm used as a short-period (SP) detector
  applied to off-line beamed SP KSRS data.

- Determine the improvements in long-period signal estimation
  by cascading previously developed techniques, developing a
  seismic filter which adapts to azimuthal wandering of incident
  signals, and designing a long-period adaptive filter which in-
  corporates a surface wave group velocity dispersion relation.

- Evaluate the discrimination capability of an expanded inter-
  active graphics system for the PDP-15 computer which in-
  cludes complex cepstrum and frequency domain spectral
  analysis, and examine the depth determination capability of
  first-zone higher mode surface waves.

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The detailed results obtained for these tasks have been pre-
sented in a series of ten technical reports. This final report summarizes
their results in Sections II through V. Section VI briefly describes the com-
puter program documentation of the Adaptive Beamforming (ABF) program
which has the capability to use Type 3 (format specification) data from the
Korean Seismic Research Station. References are given in Section VII, and
a list of all reports issued under this contract is in the Appendix.

SECTION II

EVALUATION TASKS

The majority of the results from these tasks were presented in three technical reports. A preliminary evaluation of the capabilities of the Iranian Long Period Array was given in Technical Report No. 1, and a preliminary evaluation of the five Seismic Research Observatories for which data were received was described in Technical Report No. 2. An evaluation of the detection capability of the Korean Seismic Research Station (KSRS) using an optimum seismic detector was presented in Technical Report No. 3.

A. Tasks Using Iranian Long Period Array (ILPA) Data

Because the first ILPA data was not received until the contract was well underway, this task was expanded to include the systems programming task of transferring ILPA data from the Seismic Data Analysis Center (SDAC) via the ARPANET to the Mass Store. A description of this program will be given following the summary of Technical Report No. 1.

1. Technical Report No. 1: Preliminary Evaluation of the Iranian Long Period Array

This report presented the results of a preliminary evaluation of the seven element Iranian Long Period Array (ILPA). Since data did not begin to arrive until the end of May 1976, it was necessary to sharply curtail the goals of this evaluation. In the limited time remaining in the contract period, emphasis was placed on evaluating the quality of the ILPA data and obtaining estimates of ILPA detection capability. The specific areas of investigation included the following:

- Data quality

- Sources of data errors

- Beamforming gains

- Seismic event detection thresholds

- Seismic event M_s - m_b relationships.

The results determined from this first evaluation of the Iranian Long Period Array are the following:

- The ILPA data quality is judged to be fairly good despite the various problems encountered in reading the data tapes. Of the 281 events in the data base, 84 percent were successfully processed, 1.8 percent were lost due to no data being recorded, 5.3 percent were lost to uncorrectable malfunctions, and 8.9 percent were lost to unreadable data.

- The highest gain in signal-to-noise ratio due to beamforming was 6.17 dB on the vertical component. Gains on the horizontal components averaged between 3 and 4 dB.

- The ILPA short-period 50 percent detection threshold was estimated to be 4.08 m_b units. Detection statistics used in making this estimation were obtained by visually reviewing develocorder films for events 1 through 45.

- The absolute 50 percent detection threshold for ILPA beam data is at m_b = 4.55 for Rayleigh waves and m_b = 4.48 for Love waves. Absolute detection thresholds were arrived at by counting all mixed events, events for which no data was available, events containing malfunctions, and events for which the data was unreadable as non-detections.

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- The conditional 50 percent detection threshold for ILPA beam data is $m_b = 4.09$ for Rayleigh waves and $m_b = 4.04$ for Love waves. Conditional detection thresholds were arrived at by including in the detection statistics only those events for which a detection/non-detection decision could be made.

- Beamforming lowered the conditional 50 percent detection threshold by approximately 0.15 m_b units.

- Indirect estimates of the 50 percent detection threshold made from noise samples agreed quite closely with the above described direct estimates.

- Combining the beam detection statistics of the individual components resulted in a conditional 50 percent detection threshold of $m_b = 4.01$ for the case where an event was declared detected if it was detected on one or more components. This conditional 50 percent detection threshold is $m_b = 4.13$ for the case where the event was declared detected only if it was detected on all three components.

- $M_s - m_b$ fits were computed at periods of 20, 30, and 40 seconds for earthquake data only, since the data base did not contain any presumed explosions. For this data base, the surface wave magnitude decreased with increasing period.

The major areas which must be investigated in the future to complete the evaluation of the Iranian Long Period Array are as follows:

- Noise analysis - A daily sampling of the noise field is needed to provide us with estimates of RMS noise levels, spectral content of the noise, and noise coherency.

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- Signal analysis - The data base must be greatly expanded so that regional detection capability can be estimated. Also, the work on signal-to-noise ratio gains due to beamforming should be continued and expanded.

- Discrimination capability - Depth information for the earthquakes and a suite of presumed explosions must be obtained to determine the ILPA discrimination capability.

2. ILPA Data Transfer Task

This task involved the development of software to transfer ILPA data from the SDAC via the ARPANET to the Mass Store. This work involved the following major steps:

- In determining which Data Language transfer procedure would be operationally feasible for ILPA files in the Mass Store, the UPDATE statement was found to be the most satisfactory. The ILPA port specifications were written to support this approach.

- The ILPA Long-Period, Short-Period, and Coarse Status file and port specifications were compiled and tested.

- The ILPA Satellite Tape Reformat Program which generates Long-Period, Short-Period, and Corase Status files on 9 track, 1600 bpi tape that were compatible with corresponding ILPA port specifications was designed, implemented, and tested.

- The Data Language entry procedure by which an operator may realistically transfer ILPA data files to the Mass Store was specified.

To formally complete the ILPA Data Transfer Task, a demonstration was conducted for the Air Force during which ILPA data was transferred to and retrieved from Mass Store files managed by Computer Corporation of America's (CCA) 203 Datacomputer.

B.   Technical Report No. 2: Preliminary Evaluation of the Seismic Research Observatories

It has been noted that a significant amount of long-period seismic data recorded at surface-sited instruments is degraded or obscured by wind-induced earth tilts. Tests and theoretical data indicated that this noise could be avoided by locating the sensors at a depth of 100 meters or more. This report presented the results of the work conducted to date on the evaluation of the Seismic Research Observatories, which were built to implement this observation.

The specific goals of this evaluation were as follows:

- To evaluate the quality of the short-period and long-period data recorded at each SRO.

- To investigate the short-period and long-period noise field at each SRO.

- To estimate the detection capability of each SRO.

- To estimate the discrimination capability of each SRO.

Sufficient data was available from five SRO stations to permit this evaluation in terms of the points listed above. These stations are Albuquerque, New Mexico (ANMO); Guam, Marianas Islands (GUMO); Mashhad, Iran (MAIO); Narrogin, western Australia (NWAO); and Wellington, New Zealand (SNZO).

The major results of this first evaluation of five of the SRO stations were as follows:

- In general, the quality of the SRO data is good. In the worst case for long-period data, that of the horizontal components of ANMO, the detection status of 14 percent of the signals analyzed could not be determined due to malfunctions. At the other stations, approximately 10 percent or less of the signals analyzed were lost due to malfunctions. The only short-period malfunctions were calibrations at SNZO, where 1 percent of the data could not be analyzed.

- In order of increasing magnitude, the mean short-period RMS noise values were as follows: 0.36 mμ at ANMO, 0.51 mμ at MAIO, 6.42 mμ at NWAO, 19.42 mμ at SNZO, and 31.01 mμ at GUMO. These values are uncorrected for instrument response.

- Short-period noise for all GUMO noise samples and some SNZO noise samples exceeded the system recording capability. When this happened, the noise appeared as a continuous series of spikes. This problem has been corrected by changing the quantization rate at these stations from 2000 computer counts per millimicron to 2 computer counts per millimicron.

- The lowest values of instrument response corrected long-period RMS noise were recorded at GUMO and MAIO. The values at ANMO and NWAO were slightly higher. The values for SNZO long-period RMS noise were approximately twice the size of the other stations.

- The average instrument response corrected RMS amplitude spectrum for GUMO noise shows a local maximum near 25

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seconds period. The cause of this will have to be investigated in future work.

- Based on the average RMS amplitude spectra for the five stations, the optimum bandpass filter for the SRO data has corner frequencies at 0.025 and 0.050 Hz.

- The short-period 50 percent detection threshold for events with epicentral distances ranging between 0° and 103° is 4.42 m_b units for ANMO, 4.13 m_b units for MAIO, 4.87 m_b units for NWAO, and 6.14 m_b units for SNZO. No events were detected on the GUMO short-period component. The variances on the MAIO, NWAO, and SNZO 50 percent detection thresholds were large, suggesting that more data are required at these stations to better define the detection thresholds.

- The indirect estimates of the long-period 50 percent detection threshold agree quite well with the direct estimates except at MAIO, where the indirect estimate is 0.22 m_b units higher than the direct estimate.

- The direct estimates of the long-period 50 percent detection threshold are 4.57 m_b units for ANMO, 4.51 m_b units for GUMO, 4.34 m_b units for MAIO, 4.66 m_b units for NWAO, and 4.60 m_b units for SNZO. These estimates were made using a data set from which all presumed explosions and known deep events had been deleted.

- Based on extremely limited presumed explosion data, the M_s - m_b discriminant works for presumed explosions from the Eurasian landmass but breaks down for presumed explosions from Nevada.

Future work on the evaluation of the SRO stations will be directed toward the following points:

- Evaluating all SRO stations as they become operational.

- Expanding the short-period and long-period noise data base so that one year of data is available. This will permit study of long-term noise trends.

- Building into the Interactive Seismic Processing System the capability to make instrument response corrections.

- Expanding the signal data base so that detection and discrimination results can be regionalized.

- Expanding the presumed explosion data base to improve estimates of discrimination capability.

- Obtaining depth information so that deep earthquakes can be deleted from the data base. This will improve estimates of long-period discrimination capability.

C.   Technical Report No. 3: Evaluation of Two Automatic Signal Detectors Using the Korean Seismic Research Station Short Period Array

For this study, two automatic signal detectors were applied to Korean Seismic Research Station (KSRS) short-period array data. The two detectors are (1) the conventional power detector, which computes the ratio of the short-term average beam square to the exponentially-smoothed long-term average beam square as the detector output, and (2) the Fisher detector which computes the ratio of short-term average beam square to short-term average variance across the array. The detectors were designed using a constant alarm rate algorithm for updating the detection thresholds (Lane, 1974). The objectives for this study were the following:

- Determine the seasonal detection performance using both detectors.

- Determine the detectors performance for regions of interest.

- Determine the improvement in detection capability using an automatic detector over that of an analyst.

The two detectors wei _ _ ᴀᴜᴜated for their detection performance on the basis of a constant alarm rate design operated at 10 alarms per hour. A total of 330 events in November 1974 and January-February 1976 was used as a data base. The major results of this study were the following:

- For a central Eurasia region, the 50 percent detection bodywave magnitude was approximately 4.4 m_b units using both detectors on the basis of the November data, and 4.2 m_b on the basis of the January-February data.

- For a Kurile-Kamchatka region, the 50 percent detection bodywave magnitude was approximately 4.2 m_b on the basis of January-February data.

- A single sensor power detector (using site 1) had a 50 percent detection bodywave magnitude of 4.3 m_b for all regions using the January-February data.

- Compared with the analyst's picks (using the KSRS detection logs), both detectors approached the analyst's detection capability. It was difficult to attach a precise number to this comparison because of the lack of accurate epicenter locations (hence possible large variations of arrival time).

In answer to the question of which detector is superior, a parallel study by Swindell and Snell (1976) indicates that the conventional power detector is the better detector. Because both detectors have the same

numerator in the mathematical algorithms, any difference in performance must come from the denominators. The conclusion that the conventional power detector can detect a signal more accurately than the Fisher detector lies in the fact that the algorithm in the conventional power detector was successful in freezing the long-term average (LTA, the denominator) upon the signal arrivals. This mechanism effectively prevents the contamination of signal energy in the LTA, yielding the desired greater output. The Fisher detector in the denominator computes the amplitude variance across the array. When signal similarity is not perfect, the signal component of variance degraded the performance significantly, in addition to the conventional beamforming loss (numerator).

SECTION III
SIGNAL DETECTION METHODS

The detection methods task under this contract consisted of two studies, one concerned with the determination of the detection capability of a network (Technical Report No. 4) and the other the detection capability of an array using an adaptive beamforming (ABF) algorithm (Technical Report No. 5).

A. Technical Report No. 4: Network Capability Estimation

The purpose of this study was to evaluate the effect of certain parameters upon the detection capability of a seismic network. Detection capability is defined as the lowest magnitude at which the probability of α station detections exceeds a specified limit. Since the parameters individually have a wide range, the following plan was implemented. A baseline network was established using station noise statistics furnished by Rothman (1976), and best known values for the other parameters. Then the parameters being tested were varied individually from the baseline value, and the resulting change in network detection capability was calculated.

The experiment was conducted using a modified version of the computer program NETWORTH (Wirth, 1971). Given station parameters and epicenters, both network detection threshold magnitudes and location confidence regions are computed. The parameters which significantly affect the network detection capability include the station detection threshold (SDT), possible station downtime, variance of the logarithm of the signal amplitude, and station noise levels. The major conclusions from this study were the following:

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- The station detection threshold (SDT) and the station reliability
were found to be the more critical parameters. Changing the
station detection thresholds (over the entire network) altered
the network magnitude detection capability by a constant; this
constant equalled the logarithm of the ratio of the two thresh-
olds. The relative ranking of the individual stations was unaf-
fected by changing the SDT at a network level.

- Station reliability was found to have significant impact upon net-
work capability; capability loss exceeded 0.4 m_b as reliability,
(or percentage of station uptime) dropped below 70 percent.

- Changes in the signal amplitude variance (σ_s^2) had little effect
upon detection capability for Eurasian events. For events far
removed from the network interior, detection capability de-
creased as σ_s^2 increased. However, since the network ex-
amined is primarily designed for Eurasian surveillance, this
network can be considered insensitive to changes in σ_s^2.

B.   Technical Report No. 5: Study of the Adaptive Beamforming Detector
Using the Korean Seismic Research Station Short Period Array

The adaptive beamforming (ABF) processing system is a maxi-
mum likelihood multichannel time-domain adaptive filtering beamformer. The
design goal is to minimize the filter output squared subject to unity response
constraints in the look direction. The constraints are designed for passing a
plane wave signal from the look direction in array beamforming. The objec-
tives for this study were the following:

- To determine the adaptive beamforming noise reduction rela-
tive to beamsteering and to determine the false alarm proba-
bility for the adaptive beamforming detector at the Korean
Seismic Research Station (KSRS) short-period array.

- To determine the ABF detector's performance and to estimate the increased array detection capability using the ABF detector.

The performance of the adaptive beamforming detector was evaluated using two hour-long noise samples and a total of 132 events in Eurasia. The major results of this experiment were the following:

- The noise reduction of the adaptive beamformer was about 6-10 dB gain relative to beamsteering in a lower frequency passband (0.5 - 1.1 Hz) and 2-4 dB in a higher frequency passband (1.5 - 2.4 Hz).

- Using 38 events in central Eurasia recorded in November 1974, the detection probability estimate yielded a 50 percent detection bodywave magnitude of 4.35 m_b for beamsteering and 4.24 m_b for the ABF detector. For 94 events in the Kurile-Kamchatka region recorded in January-February 1976, the 50 percent detection bodywave magnitude was 4.10 m_b for beamsteering and 4.12 m_b for the ABF detector.

- A simulation study indicated that signal degradation using the ABF algorithm increases for the lower single-channel input signal-to-noise ratios. (This explains the dissappointing results given above.) Freezing the ABF update mechanism prevented this signal degradation somewhat, but for actual applicability as a detector this degradation depends on whether or not the noise is propagating in the look direction. Future work will be directed toward minimizing this signal degradation.

SECTION IV
SIGNAL ESTIMATION TECHNIQUES

The results of this task are presented in three reports. The optimizing of three important signal processors for possible cascading is presented in Technical Report No. 6. An improved version of the three component adaptive processor is studied in Technical Report No. 7, and a time-variant Wiener filter utilizing the regionally dispersive characteristics of long-period surface waves is developed in Technical Report No. 8.

A.   Technical Report No. 6: Development of Three Signal Processing Techniques

This report describes the performance of three important processors for seismic data: the Wiener filter, the matched filter, and the three component adaptive (TCA) processor. Each has been optimized as far as possible for cascading in the immediate future.

The data used here were single-site Alaska Long Period Array (ALPA) signals and noise samples. Single-site data were used because the detection problem is more severe for a single instrument than for an array, and because the trend at present is toward deployment of single-site instrumentation (Seismic Research Observatories) and small arrays (Iranian Long Period Array). ALPA data were used because they are of high quality and because the nature of noise and signals at ALPA is well known.

Synthetic data were prepared by selecting a 2048-point segment of seismic noise, sampled every two seconds, and adding to it a suitably scaled signal, originally recorded at high signal-to-noise ratio (SNR), to form

a composite trace. The ratio of the scaled peak to the root-mean-square (RMS) value of the noise preceding the time at which the signal was added was the true input signal-to-noise ratio. For the matched and Wiener filters, different scale factors were used for each trace so that all had the same SNR. For the TCA, a common scale factor was used so that the signal was not distorted. This procedure has the advantage over use of signals as recorded that the true SNR and peak arrival time are known exactly, and can be varied by the experimenter.

The general experimental procedure was as follows. The test event was buried in noise at various known SNR's, and the processor under study applied to the composite trace. The ratio of the largest peak in the signal arrival interval to the RMS value of the preceding noise was calculated. The SNR was also calculated for the same composite trace filtered between 0.024 Hz and 0.059 Hz, the frequency range where the SNR of seismic events is expected to be large. The difference (in dB) between these ratios was the gain of the processor over the bandpass filter.

It is useful to present gains rather than absolute SNR's because gains do not increase indefinitely with input SNR, but saturate at some maximum value. The bandpass filter was chosen as a standard because it is a routine form of signal improvement whose performance is well known.

At low values of input SNR the signal is so far below the noise that the peak of the processor output is not contributed by the signal. Consequently, the gain is not a function of the input SNR. At sufficient input SNR, the processor output is determined by the signal, although, hopefully, the bandpass filters' output is still due to noise. At this point the gain of the processor begins to increase. At some higher SNR the bandpass filter peak is due to the signal, and thereafter little gain is obtained. In some cases the gain may decrease. In any case, the SNR gain reaches a maximum, and this maximum gain is taken here as a measure of processor performance.

The optimization of these processors yielded the following results:

- The Wiener filter used a synthetic reference power spectrum and had its greatest improvement in signal-to-noise ratio when correlation terms between the signal and noise were ignored. The gain of this filter over the bandpass filter ranged from 2 to 6 dB, depending on the noise and signal samples examined.

- A prewhitened matched filter using the same reference event (as the Wiener filter) displayed from 5 to 10 dB improvement over the bandpass filter. By the nature of the matched and Wiener filters, the matched filter is expected to have better gain.

- The TCA yielded from 10 to 17 dB improvement over the bandpass filter when a weighting function based on the probability distribution function of the variables of the surface wave particle motion was employed.

- For all processors the gains found when signals were held constant were more consistent than when noise samples were held constant. This is presumably because details of the noise are less important in determining gain than are details of the signal being sought.

B.   Technical Report No. 7: Evaluation of the Three-Component Adaptive Processor

The three-component adaptive processor (TCA) was developed at the Lamont Geophysical Observatory (Shimshoni and Smith, 1964) and was evaluated for single-site and beam data by Texas Instruments Incorporated (Lane, 1973). This processor, designed to improve the detectability of long-

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period Rayleigh and Love waves, takes advantage of the known phase relation-
ships among the three mutually perpendicular long-period seismometer traces.
Improvements in the signal-to-noise ratio (SNR) can be achieved when these
phase relationships are utilized in the processor design.

The evaluation of the original TCA processor (Lane, 1973) re-
vealed that improvements in signal-to-noise ratio are much greater for Ray-
leigh wave processing than for Love wave processing. This is due to two fac-
tors. First, Love wave energy may arrive as much as 20° off the great cir-
cle azimuth, and the TCA processor suppresses this motion as though it were
noise. Second, the TCA processor confuses the radial motion of the Rayleigh
wave with off-azimuth Love waves, and suppresses whatever genuine Love
wave energy which is present. Thus, the TCA processor has shown itself to
be less effective in separating Love waves than Rayleigh waves from noise.

This study describes an attempt to rectify this situation. The
TCA processor is modified to track the incoming Love wave in azimuth and to
pass its entire duration. This is accomplished by using in the design of the
transverse component filter the additional information contained in the phase
relationships of the Rayleigh waves. The evaluation of this modification of
the TCA processor used both synthetic and real data. The synthetic data con-
sisted of known signals with high signal-to-noise ratios buried in seismic
noise. These were used to study the signal-to-noise ratio improvement char-
acteristics of the processor. Part of the real data used consisted of hour-
long noise samples, which were used to determine signal detection criteria
and false-alarm characteristics of the processor. The remainder of the real
data consisted of single-site and beam data recorded at the Alaskan Long Per-
iod Array (ALPA). This data was used to study the detection performance of
the processor.

To allow direct comparisons between the original and new Love
wave processors, the original Love wave processor was re-evaluated using

the same data base as was used for the evaluation of the new Love wave processor. The Rayleigh wave processor was also re-evaluated, since the necessary data processing for this was performed automatically with the Love wave data processing. Use of the larger data base should improve previous estimates of Rayleigh wave detection capability improvement due to application of the TCA processor.

The following results were found during the course of this evaluation of the TCA processor:

- The most effective form of the new Love wave TCA processor contains rotation of the Love wave frequency components about the vertical axis to the transverse component with an accept-reject limit placed on the Love wave arrival azimuth.

- At 12 dB true signal-to-noise ratio, we can expect 7-9 dB gain for Rayleigh waves and 6-7 dB gain for Love waves from the original TCA processor on single-site data.

- At 12 dB true signal-to-noise ratio, we can expect about 9 dB gain for Love waves from the new TCA processor on single-site data.

- Only low or negative gains can be expected from either version of the TCA processor when applied to beam data.

- Use of the original TCA processor on single-site data lowered the fifty percent Rayleigh wave detection threshold by about 0.25 - 0.4 m_b units and the fifty percent Love wave detection threshold by about 0.15 m_b units.

- Use of the new Love wave TCA processor on single-site data lowered the fifty percent Love wave detection threshold by about 0.35 m_b units.

- Use of the original TCA processor on beam data yielded a small (0.15 m_b unit) improvement in the Rayleigh wave fifty percent detection threshold and essentially no change in the Love wave fifty percent detection threshold.

- Use of the new Love wave TCA processor on beam data yielded essentially no change in the Love wave fifty percent detection threshold.

The above points make it clear that the original Rayleigh wave TCA processor and the new Love wave TCA processor are effective when applied to single-site data. No version is effective when applied to beam data.

C.   Technical Report No. 8: Time-Variant Wiener Filter for Dispersed Waveforms

The dispersive characteristics of the surface waves generated by seismic events have been used in various forms in the signal processing and analysis of long-period (LP) waveforms. For instance, correlation processes, such as reference waveform and chirp waveform matched filtering (MF), compress the available signal energy while averaging the supposedly random noise, to yield correlation peaks of high signal-to-noise ratio (SNR). Because of the signal energy compression in time, these techniques cannot be used to obtain an improved estimate of the original signal as a function of time, and are therefore mainly used for detection purposes.

This study presented a method to enhance the estimate of an LP signal as a function of time, through utilization of its dispersive characteristics. We call this technique dispersion-related filtering (DRF).

The most elementary form of DRF consists of time-variant narrowband filtering along the signal's presumed dispersion curve. In this

manner considerably more noise energy can be rejected than in stationary bandpass filtering of the waveform over the entire expected signal frequency band. This method has the inherent property, however, to generate partial chirp waveforms, which can be mistaken for signals, from any broadband input, including pure noise. For this reason, DRF is not well suited for signal detection; its main function is signal estimation.

For a given region-station combination the expected dispersion curve may be obtained by overlaying the time-variant signal spectra measured from strong events in the given region. The spread or variance of the dispersion curve ensemble and the signal bandwidth at each point in time then determine the bandwidth to be applied at each point along the dispersion curve.

The signal estimate can be further improved by performing time-variant Wiener filtering (TVWF); i.e., for each point along the dispersion curve the expected signal power and the expected noise power are balanced to yield a signal estimate of minimum mean square error. In particular, TVWF tends to reduce signal over-estimation at frequencies of relatively high noise power, e.g., at 0.06 Hz (17-sec micro-seismic noise), and at frequencies around 0.02 Hz (50 sec).

Besides ambient noise rejection, DRF is theoretically capable of separating multiple dispersed signals, provided that the individual dispersion curves can be resolved by spectral analysis.

It is clear that in all cases the DRF and TVWF performance depends largely on the effectiveness and reliability of the spectral analysis method applied. Therefore, part of this study's effort was dedicated to the use of a high-resolution spectral analysis method, the maximum entropy spectrum (MES) technique (Burg, 1968).

In this study the DRF and TVWF methods were developed and tested on synthetic chirp waveforms and on beamed waveforms from Sinkiang

Province seismic events, recorded at the Alaskan Long Period Array (ALPA). The use of this data base permits comparison with the results of a previous matched filtering performance study (Unger, 1973). The emphasis was placed on the feasibility of dispersion-related filtering and on its potential and limitations to improve the estimation of long-period seismic signals from noisy wave waveforms.

These experiments led to the following conclusions and indications:

- The MES results are somewhat ambiguous and depend strongly on the MES algorithm parameters used (sample rate, waveform gate length, number of error prediction filter coefficients).

- The definition of regional dispersion curves is subject to an analyst's spectral interpretation.

- Despite some ambiguity, the MES technique provides high-resolution group velocity curves.

- The TVWF is effective as a signal estimator rather than as a detector.

- The TVWF enhances the estimation of signals at least down to 0 dB RMS SNR. In particular, it considerably improves the measurability of surface wave magnitudes.

- Below 0 dB RMS SNR, the estimates may become unreliable due to non-stationary coherent noise and the difficulty of estimating the waveform's SNR, which is a sensitive parameter in the Wiener filter design.

- The TVWF noise rejection over stationary bandpass filtering ranges from 3 to 9 dB depending on the inherent bandwidth of a signal along its dispersion curve.

IV-8

● Dispersion-related filtering is based on narrowband filtering about a known dispersion curve; narrowband filtering of time-variant waveforms produces amplitude and phase errors. The amplitude errors, which mainly depend on the filter bandwidth and the dispersion rate, can in general be corrected to within 1 dB; in unfavorable cases the remaining error may be as much as 2.5 dB. The phase error could not be corrected, but appears to be small for natural seismic signals.

● The filter's separation power is limited by the widths of the sin x/x main lobes and the presence of side lobes, determined by the filter bandwidth. For signals with parallel dispersion curves the minimum separation interval and the corresponding bandwidth are determined by the dispersion rate. For a 4.10^{-5} Hz/sec dispersion rate, signals separated by 200 sec can be resolved with a bandwidth of 0.008 Hz; however, the output contains about 50 percent amplitude distortion due to sin x/x side lobe interference. Signals with non-parallel dispersion curves appear to be better separable.

● The TVWF requires that the signal start time be known; this may be found with any, or a combination, of the following methods:

- deduction from given source location and time
- sliding the TVWF dispersion band through the waveform and searching for the maximum RMS value
- MES analysis
- instantaneous signal phase detection.

The second and third method appear to be most accurate, but are more time and core consuming.

● In the present design the filtering is performed in the frequency domain; this requires in principle one inverse Fourier transform for every dispersion point of non-overlapping bandwidths. For a signal with a 1000-sec dispersion, sampled at 2-sec intervals, with 5.10^{-4} Hz frequency increments and 0.04 Hz bandwidth, this amounts to more than 80 inverse transforms. Alternatively, one may conceive the filter design as a time-domain convolution, using a tuned filter technique; this method should be considerably faster.

● The TVWF signal enhancement should prove useful in magnitude measurement, $M_s - m_b$ discrimination, Love wave versus Rayleigh wave energy measurement, source parameter studies, propagation and geological structure studies, and possibly other signal analysis and classification techniques.

● A statistical filter performance evaluation using an ensemble of combinations of noise samples and known signals is required to establish the full range of filter performance characteristics.

SECTION V

DISCRIMINATION TASK

This task involved two quite different approaches to the problem of discriminating between earthquakes and underground nuclear explosions. The first approach involved the augmentation of the Interactive Seismic Processing System (ISPS) developed by Ringdal and Shaub (1974) with a module which performs several discrimination calculations. The overall purpose of this system is to provide an interactive graphics capability for the purpose of detecting and analyzing seismic waveforms. The second approach involved the examination of first-zone surface wave spectra for higher mode generation, and the possible use of this mode to determine depth (e. g. , discriminate by source depth estimation).

A.   Technical Report No. 9: Design, Simulated Operation, and Evaluation of a Short-Period Seismic Discrimination Processor in the Context of a World-Wide Seismic Surveillance System

In designing a world-wide seismic surveillance system, one difficult design problem is to provide seismic analyst-computer interaction needed to analyze waveforms and to reliably classify the seismic events as possible explosions. Efficiency is required to keep up with the daily load of events subjected to classification processing. Flexibility is required to quickly alter operating procedures. It is anticipated that such changes will be needed until our discrimination capability is sufficient to identify explosions originated from any region of interest.

To partially fulfill these requirements, a special purpose interactive seismic processing module was developed on a PDP-15

minicomputer for Short Period Earthquake/Explosion Discrimination (SPEED). This processing module was imbedded in a simulated special purpose seismic operating system. This system, the Interactive Seismic Processing System (ISPS), was developed by Ringdal and Shaub (1974). The module SPEED consists of three discriminant calculations. In Figure V-1, the first one of the discriminant functions performs cepstrum analysis; the second, variable frequency magnitude (VFM) analysis; and the last, corner frequency analysis (CF). The three functions of SPEED - cepstrum, VFM, and CF - are described as follows:

- The cepstrum analysis is subdivided into three interactive subroutines. SUB1 adjusts start time or exponentially tapers the data as described by the analyst. SUB2 separates the signal and echo by trial and error deconvolution. SUB3 generates a residual seismogram and sets up CEPSTRUM to pick later phases (e.g., multiple explosions), if desired by the analyst. The statistics generated for discrimination are the time delay of the echo, reflection coefficient, correlation coefficient between the echo and the first arrival, and the residual noise when the estimate of the echo and first arrival are removed from the original data.

- The VFM analysis in SUB4 removes the exponential taper from the first arrival signal estimate derived from CEPSTRUM. In SUB5 it computes the high and low frequency dependent magnitudes from the corresponding semi-log-signal spectrum display corrected for absorption.

- The CF analysis in SUB6 can measure up to four corner frequencies, amplitudes, and roll-offs from the log amplitude versus log frequency spectrum of the signal transmission corrected for absorption.

SHORT-PERIOD EARTHQUAKE/EXPLOSION DISCRIMINATOR
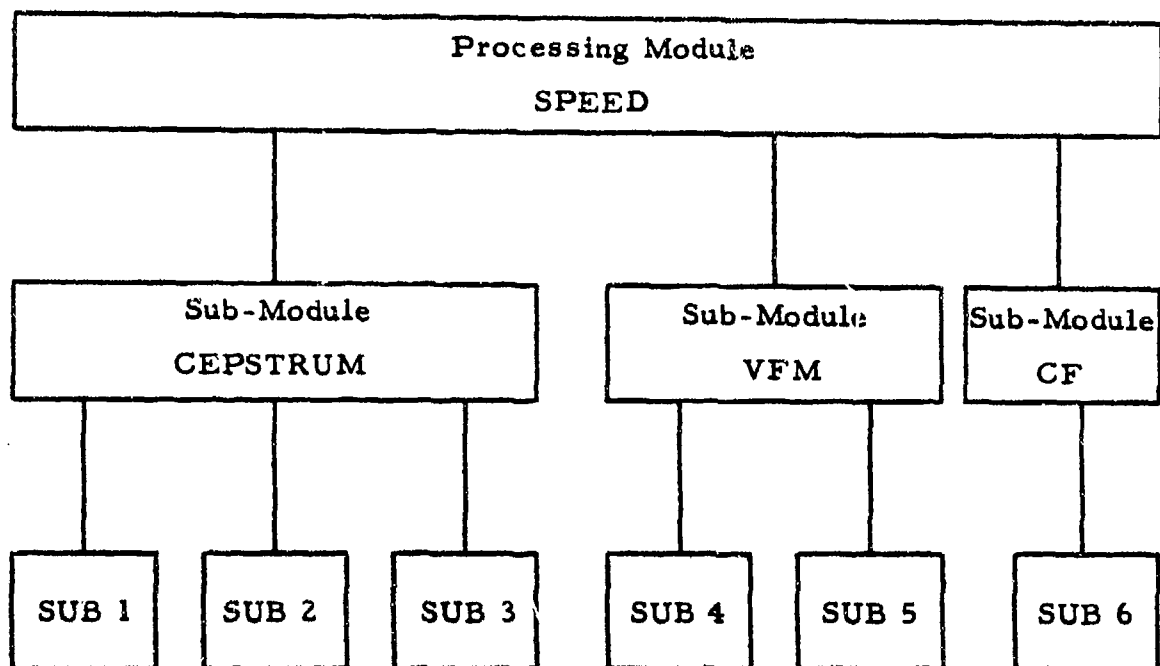
SUB 1 - Conditions Data For Cepstrum Analysis

SUB 2 - Separates Signal And Echo

SUB 3 - Computes Residual Seismogram

SUB 4 - Conditions Data For Spectral Analysis

SUB 5 - Computes Variable Frequency Magnitudes

SUB 6 - Computes Corner Frequency And Amplitude From Log-Log
          Spectrum Plot

FIGURE V-1

SHORT-PERIOD EARTHQUAKE/EXPLOSION DISCRIMINATOR

Support programs were developed to use an IBM 360/44 computer to reduce all of the station component seismograms to a single representative event waveform. An option is provided for inputting the single representative event waveform into SPEED either corrected for or uncorrected for system response. The examples analyzed were corrected to broadband ground displacement between 0.25 and 5.0 Hz.

The SPEED processing module as presently configured can be programmed to perform any one of many discrimination procedures by a prescribed sequence of button pushing. To obtain baseline performance data, one very simple and reproducible discrimination processing procedure was prescribed. A data base of 35 events, including 20 earthquakes and 15 presumed explosions in the magnitude range between 4.4 and 6.1, were run through the SPEED processor. For each event, the discrimination measurements obtained from SPEED were processed by multivariate discrimination analysis of frequency dependent magnitude measurements to derive a two-component discriminant output. One component was optimized to discriminate central Asian presumed explosions. The other component was optimized to discriminate western United States presumed explosions. The performance results obtained by analyzing the length of the two component discriminant vectors clearly separated earthquakes from presumed explosion events from the two regions. Assuming normal statistics, it is expected that 90 percent of the presumed explosions can be detected with a probability of false positive identification of 0.004. Two outliers were obtained, one from each presumed explosion region. This indicates the need for more discriminant components in the measured discriminant vector, and possibly more components in the resultant discriminant space needed to identify all explosions by region or medium type.

B.   Technical Report No. 10: Applications of Higher Mode Surface
       Waves

It is well known that earthquakes and underground nuclear ex-
plosions radiate energy in the form of surface waves which propagate at velo-
cities which are the roots of equations relating frequency, seismic velocity,
and propagation velocity (Harkrider, 1970). There are an infinite number of
roots to this equation both for Love and Rayleigh waves, and in principle
every seismic event is accompanied by energy propagating in each of the
modes corresponding to these roots. In practice, only the fundamental mode
(i. e. , R_0, L_0) with lowest velocity is excited with large enough amplitude to
be useful for most detection and discrimination problems. In this study, we
attempted to obtain information about the source from hitherto unused higher
mode surface waves.

Two uses for higher modes were examined, both employing the
first higher mode Love wave (denoted L_1). This mode was chosen because its
amplitude is expected to be larger than that of any other higher mode Love
wave, and because it varies more in amplitude with period than does the first
higher mode Rayleigh wave, the other possible candidate for this study.

A number of studies (Turnbull, et al., 1973, Turnbull, 1976)
have described a procedure for fitting measured seismic spectral amplitudes
to theoretical source spectra. Seismograms recorded at stations with good
azimuthal distribution about the source (if possible) are narrowband filtered
to estimate the Fourier component attributable at that period to the arrival of
interest (Alexander, 1963). These spectral amplitudes were corrected for the
earth's attenuation, structure, and for distance, and the mean square differ-
ence between them and those predicted by a model is minimized as a function
of the model parameters. The parameter most sensitive to this fitting pro-
cess is the source depth, so that this method can be used to discriminate be-
tween deep and shallow events.

The radiation pattern for higher mode surface waves is similar to that of the fundamental mode, since the various modes are characteristic of the medium rather than the source (Turnbull, 1976). The amplitude response of the earth is different for different modes, due to their different wavenumbers, and this response can be calculated for a given earth model. Finally, the attenuation of the earth may be different for various modes, and must be found by experiment. Then higher mode amplitudes may be used to calculate source depth in the same way as are fundamental mode amplitudes.

It was attractive to look for another discriminant based on higher modes, and the amplitude ratio L_1/L_0 was investigated for this purpose. This ratio was calculated for source models at various orientations for a range of periods from 6 to 15 seconds, for several earth models. Under the appropriate models the ratio's level changed with orientation but its general features as a function of period did not, and that the ratio displayed features below 15 seconds which occur at lower periods for lower velocity surface layers. Measurement of this ratio should then give an indication of the seismic velocity at the source.

Surface waves from a number of events were examined for the presence of higher mode energy. Amplitudes of the first higher mode Love wave were measured, corrected for distance, instrument response, and attenuation, and fit to a model of the fault plane and propagation path. The results suggested that this mode, the most promising for the purpose, has no capability for depth discrimination, at least in North America. The reasons for this failure are the high value of the energy attenuation coefficient and the lack of a good source model.

In order to discriminate between different source structures, the ratio L_1/L_0 was calculated as a function of period both experimentally from the observed data and theoretically from two source models. Agreement

between observation and theory was more encouraging than for the spectral fitting method, but was still short of satisfactory.

It is recommended that any further study of the utility of higher modes for discrimination be directed toward data from a region of low attenuation coefficient and well known simple structure.

SECTION VI
COMPUTER PROGRAM DOCUMENTATION

The documentation for the adaptive beamforming program
(ABF) developed by Texas Instruments Incorporated for the Air Force Tech-
nical Applications Center (AFTAC) under Contract Number F08606-74-C-
0033 was modified to include Korean Research Seismic Station (KSRS) short-
period array type 3 formatted data, as well as the original type 1 formatted
data. As mentioned in the original documentation (1974), this program has
the following significant features:

- Several covergence rates can be analyzed in one pass of the
  input data.

- Options exist for inputting vertical component data from the
  ALPA, NORSAR, and LASA long-period arrays and the Korean
  short-period array.

- Options exist for combining two separate events after scaling
  and rotating the events to the desired azimuths so that inter-
  fering events may be analyzed; the adaptive filters are design-
  ed on the composite trace and the user is allowed to view the
  effect of the filters on each event.

SECTION VII

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1974 - Documentation of Adaptive Beamforming Program for Interfering Event Studies, AFTAC Project VT/4705, AFTAC Contract Number F08606-74-C-0033, Texas Instruments Incorporated, Dallas, Texas.

APPENDIX A

LIST OF REPORTS FROM CONTRACT
F08606-76-C-0011

A.   QUARTERLY REPORTS

1.   Quarterly Report No. 1, covering the period 15 July 1975 to 15 October 1975, Texas Instruments Report No. ALEX(01)-QR-76-01, 15 October 1975.

2.   Quarterly Report No. 2, covering the period 15 October 1975 to 15 January 1976, Texas Instruments Report No. ALEX(01)-QR-76-02, 15 January 1976.

3.   Quarterly Report No. 3, covering the period 10 January 1976 to 10 April 1976, Texas Instruments Report No. ALEX(01)-QR-76-03, 10 April 1976.

4.   Quarterly Report No. 4, covering the period 10 April 1976 to 10 July 1976, Texas Instruments Report No. ALEX(01)-QR-76-04, 10 July 1976.

5.   Quarterly Report No. 5, covering the period 10 July 1976 to 10 October 1976, Texas Instruments Report No. ALEX(01)-QR-76-05, 10 October 1976.

B.   TECHNICAL REPORTS

1.   Preliminary Evaluation of the Iranian Long Period Array, by Alan C. Strauss, Texas Instruments Report No. ALEX(01)-TR-76-01, 29 October 1976.

2. Preliminary Evaluation of the Seismic Research Observatories, by Alan C. Strauss, Texas Instruments Report No. ALEX(01)-TR-76-02, 29 October 1976.

3. Evaluation of Two Automatic Signal Detectors Using the Korean Seismic Research Station Short-Period Array, by Wen-Wu Shen, Texas Instruments Report No. ALEX(01)-TR-76-03, 29 October 1976.

4. Network Capability Estimation, by Nolan S. Snell, Texas Instruments Report No. ALEX(01)-TR-76-04, 24 September 1976.

5. Study of the Adaptive Beamforming Detector Using the Korean Seismic Research Station Short-Period Array, by Wen-Wu Shen, Texas Instruments Report No. ALEX(01)-TR-76-05, 29 October 1976.

6. Development of Three Signal Processing Techniques, by Stephen S. Lane, Texas Instruments Report No. ALEX(01)-TR-76-06, 29 October 1976.

7. Evaluation of the Improved Three Component Adaptive Processor, by Alan C. Strauss, Texas Instruments Report No. ALEX(01)-TR-76-07, 24 September 1976.

8. Time-Variant Wiener Filter for Dispersed Waveforms, by Rudolf Unger, Texas Instruments Report No. ALEX(01)-TR-76-08, 29 October 1976.

9. Design, Simulated Operation, and Evaluation of a Short-Period Seismic Discrimination Processor in the Context of a World-Wide Seismic Surveillance System, by Robert L. Sax, Texas Instruments Report No. ALEX(01)-TR-76-09, 29 October 1976.

10. Applications of Higher Mode Surface Waves, by Stephen S. Lane, Texas Instruments Report No. ALEX(01)-TR-76-10, 11 October 1976.

C.   DOCUMENTATION

1.   Documentation of the Adaptive Beamforming Program For
      Interfering Event Studies, Change 1, 20 August 1976.

D.   FINAL REPORT

1.   Final Report, VELA Network Evaluation and Automatic Pro-
      cessing Research, by Lawrence S. Turnbull, Jr., and Staff,
      Texas Instruments Report No. ALEX(01)-FR-76-01.